

SUBSURFACE INVESTIGATION USING GROUND PENETRATING RADAR

Steve Cardimona

Department of Geology and Geophysics, University of Missouri-Rolla, Rolla, MO

ABSTRACT

The ground penetrating radar geophysical method is a rapid, high-resolution tool for non-invasive investigation. Ground penetrating radar records microwave radiation that passes through the ground and is returned to the surface. The radar waves propagate at velocities that are dependent upon the dielectric constant of the subsurface, and reflections are caused by changes in the dielectric constant that are due to changes in the subsurface medium. A transmitter sends a microwave signal into the subsurface, and the time it takes energy to return to the surface relates to the depth at which the energy was reflected. Thus, interpretation of this reflected energy yields information on structural variation of the near subsurface. Ground penetrating radar transmitters operate in the megahertz range, and the choice of source signal peak frequency helps to determine the expected depth of penetration and resolution. Higher frequency sources will offer greater vertical resolution of structure but will not penetrate as deep as lower frequency sources. The choice of appropriate source will be target and project-goal dependent. Data are most often collected along a survey profile, so that plots of the recorded signals with respect to survey position and travel-time can be associated with images of geologic structure as a function of horizontal position and depth. Ground penetrating radar can be collected fairly rapidly, and initial interpretations can be made with minimal data processing, making the use of ground penetrating radar for shallow geophysical investigation quite cost-effective.

INTRODUCTION

Detailed structural interpretation can be important for hydrological and geotechnical applications such as determining soil and bedrock characteristics in the shallow subsurface. In addition, high-resolution imaging is important for monitoring structural integrity of buildings, mine walls, roadways and bridges. Ground penetrating radar (GPR) is the only geophysical technique that can offer the horizontal and vertical resolution necessary for many of these applications.

The GPR method records microwave radiation that passes through the ground and is returned to the surface. A transmitter sends a microwave signal into the subsurface, and the radar waves propagate at velocities that are dependent upon the dielectric constant (also known as relative permittivity) of the subsurface medium. Changes in the dielectric constant that are due to changes in the subsurface materials cause the radar waves to reflect, and the time it takes energy to return to the surface relates to the depth at which the energy was reflected. Thus, interpretation of this reflected energy yields information on structural variation of the near subsurface.

Because GPR transmitting antennae operate in the megahertz range, the waves that propagate tend to have wavelengths on the order of 1m or less. Horizontal and vertical resolution are dependent upon the wavelength, such that the smaller the wavelength, the better the resolution. Although higher frequency sources will yield smaller wavelengths (better resolution), the higher frequency signals will not penetrate as deep as lower frequencies. Thus a careful choice must be made regarding the GPR antennae to use in a survey based on expected target and the project goals. Once a source antenna is chosen for a particular survey, GPR data can be collected fairly rapidly. The GPR method can be used for reconnaissance (anomaly location) as well as for more detailed study (structural interpretation).

This paper is meant to be an overview of pertinent ideas that relate to the GPR method. We suggest the reader refer to the overviews in Hempen and Hatheway (1992) and Daniels (1989), and the comprehensive introductory text by Daniels (1996) for more discussion of the related topics.

BACKGROUND

The fact that radar waves are basically the same as light waves may leave the casual reader feeling a little confused; however, the ability to use radar waves to image the near subsurface of the earth defines the first principal under which the GPR method operates:

Principal #1--> Radar (electromagnetic) waves *do* pass through earth materials.

The visual region is only a portion of the wide spectrum (different frequency components) of electromagnetic radiation. Microwave radiation (radar) with frequencies on the order 10MHz to 1000MHz is not in the visual spectrum, but will propagate at the speed of light in a vacuum just as all other electromagnetic radiation. The subsurface of the earth is, of course, not a vacuum, which introduces the second important principal for understanding GPR:

Principal #2--> Each material is described by specific electrical properties.

These properties are magnetic permeability, electrical conductivity, and electric permittivity. Most earth materials (soils and rocks) are non-magnetic, so that the permeability of free space is a good representation for the magnetic permeability of the subsurface. The conductivity is important because it controls the amount of energy lost in the propagating signal (due to conductive attenuation). When the permittivity of the medium (ϵ) is compared to the permittivity of free space (ϵ_0), we get a value for the relative permittivity (ϵ_r), or dielectric constant (k), of the material

$$\epsilon_r = k = \frac{\epsilon}{\epsilon_0}.$$

The dielectric constant defines the index of refraction of the medium and is a material constant which controls the speed of electromagnetic waves in the material.

$$v = \frac{c}{\sqrt{k}},$$

where c is the speed of light in air and v is the velocity of the electromagnetic energy in the subsurface medium. Thus, changes in the subsurface material will effect the index of refraction, and reflected energy will be produced related to the contrast in the dielectric constant across a boundary between two materials. Table 1 lists typical dielectric constants for some common materials. Note that the dielectric constant is controlled mainly by water content.

Table 1

<u>Material</u>	<u>Typical Dielectric Constant</u>	<u>Radar propagation velocity (m/ns)</u>
Air	1	0.30
Water	81	0.033
Granite	9	0.10
Limestone	6	0.12
Sandstone	4	0.15
Rocks	4-12	0.15-0.087
Dry sand	4-6	0.15-0.12
Wet sand	30	0.055
Dry clay	8	0.11
Wet clay	33	0.052
Dry soils	3-8	0.17-0.11
Wet soils	4-40	0.15-0.047
Asphalt	3-6	0.17-0.12
Concrete	9-12	0.10-0.087

Most GPR transmitters are pulse-radar, operating in the time-domain to send a time-pulse of energy (source wavelet) propagating into the subsurface. When a GPR transmitter sends a signal into the subsurface, an expanding spherical wavefront describes the propagating electromagnetic energy as it travels away from the source (Figure 1). This can be listed as our third principal:

Principal #3--> Pulse-radar propagates time-pulse energy away from source along an expanding wavefront.

Although principal #3 describes the true physics of the propagating electromagnetic wavefield, we make an approximation to this by introducing the concept of the ray (Figure 1):

Approximation #1--> A single ray path represents the wavefield traveling in a specific (ray) direction.

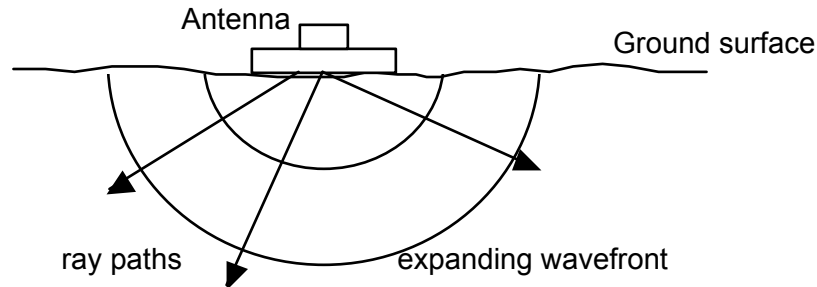


Figure 1. Electromagnetic energy propagating away from the source can be described by an expanding wavefront. Ray paths help to describe energy traveling in any one particular direction.

We can then describe the entire wavefield by an infinite number of rays traveling in all directions away from the source. This reasonable approximation (ray theory) allows us to more easily describe the traveling wave in the subsurface. The radiation pattern for a GPR antenna is actually more complex than shown in Figure 1. Although most GPR antennae are shielded, some electromagnetic energy does travel upward into the air. Also, radar antennae do not have simple hemispherical radiation patterns (Figure 2).

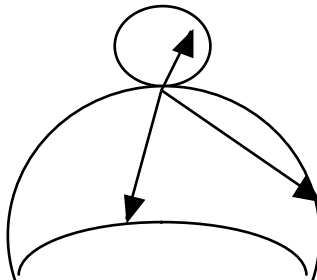


Figure 2. Radiation pattern for electromagnetic energy propagating away from GPR antenna on surface of the Earth. Energy propagating into the air is non-zero, and wavefronts in subsurface are not simple.

When ray paths intersect boundaries between materials, the energy in the traveling wave is partitioned between reflected and transmitted waves. Thus we have our fourth operating principal:

Principal #4--> Inhomogeneity (variations in electrical properties) cause reflections.

Snell' Law of ray theory describes how the reflected and transmitted (refracted) waves propagate away from the boundary. Of course, it is the reflections that propagate back to the surface that are recorded on the GPR receiver. After a GPR survey is conducted, data are normally presented as plots of the returned signal as a function of time (associated with depth) and survey position (horizontal coordinate). This 2-D profile is then interpreted as an image of structural variation below the survey line, leading us to our second approximation:

Approximation #2: All inhomogeneity is directly below the GPR survey line.

We make this assumption because our normal form of data presentation displays an image of structure which has placed all returned energy below the survey line in the 2-D profile. However, this approximation is invalid. The electromagnetic radiation travels in all directions away from the source, not just in the plane described by the horizontal survey coordinate and the depth of investigation. This energy will be scattered

off of discontinuities that are not directly below the survey line, but the energy will still be recorded by the survey receiver. Plotting the data in 2-D cross-sections is truly a matter only of convenience. Care must be taken during interpretation as some of the features in the 2-D profile of subsurface structure will be artifacts due to the energy scattered from outside the imaging plane.

DATA COLLECTION

Survey design for GPR work requires the determination of what type of survey one wishes to undertake and what operating frequency one will use for the source, although this may be a function of equipment availability. The most common survey technique used with the GPR method is common offset profiling. Certain GPR instruments are designed to be able to collect common midpoint survey data also. Higher frequency sources will offer greater resolution of structure but will not penetrate as deep as lower frequency sources.

Common offset profiling

The most common survey technique used with the GPR method is common offset profiling. In this technique, the transmitting and receiving antennae are kept a fixed distance apart, and progressively moved along a survey line to record returned signals from the subsurface. The result is a data set presented in a 2-D profile with intent to create an image of subsurface structure. There are two types of GPR systems available to be used to collect common offset data: monostatic and bistatic units.

A true monostatic radar system uses the same antenna as the source and the receiving antenna; however, radar instruments that have both transmitting and receiving antennae housed within the same instrument are normally considered to be coincident and monostatic because they cannot be separated. Monostatic GPR units allow for rapid data collection. Instruments are normally pulled along a profile, yielding continuous data collection (Figure 3). The result is very small horizontal sampling (good horizontal resolution), but very large data files. High frequency units are quite light and portable, but lower frequency units are large and heavy, creating logistic difficulties.

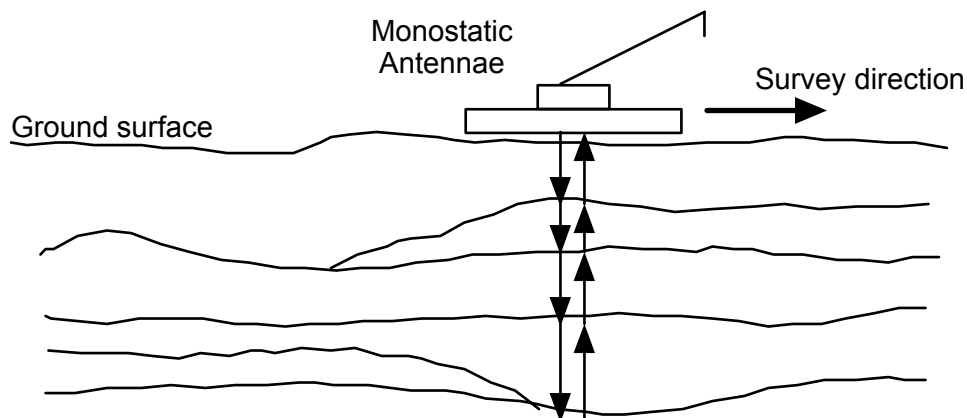


Figure 3. A monostatic GPR unit houses both transmitting and receiving antennae in the same instrument. The antennae are pulled along the profile, and data are interpreted to be normal incidence reflection signals.

Bistatic GPR antennae are separate instruments (Figure 4). With bistatic antennae, the source-receiver offset (antenna separation) is held constant for common offset profiling, and this offset can be optimized for best results. Data files are small and easily manageable, but this is because the horizontal sample interval is normally chosen to be large (at discrete offset positions) which can reduce lateral resolution. Increasing the horizontal sample rate (decreasing the survey step interval) increases the time necessary to complete the survey, as every new survey location represents a discrete reading that must be made.

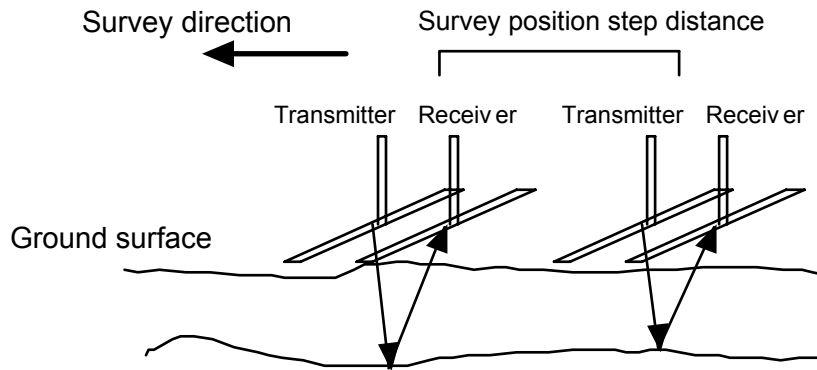


Figure 4. Bistatic GPR instrumentation includes two separate transmitting and receiving antennae units. The antennae are placed at discrete locations along the profile, and data are interpreted to be near-normal incidence reflection signals.

Common midpoint survey

A common midpoint (CMP) survey is one in which bistatic antennae are progressively moved away from each other, collecting data at each new, more distant position, but keeping the center between the two antennae fixed. This type of data can aid in interpretation by helping to determine the electromagnetic wave velocity. The change in travel time (the moveout) as a function of increasing offset between the two antennae is directly related to the electromagnetic wave velocity of the subsurface.

Obviously, this exact type of survey cannot be done with a monostatic GPR unit. Surveys with monostatic units must use another technique to estimate subsurface velocities. Pulling a monostatic unit over a known subsurface feature can give an estimate of velocity either by simple calculation (known depth divided by measured travel-time), or by measuring the moveout of a diffracted arrival from the target (Figure 5). The latter yields a monostatic version of a CMP. Again, this moveout is directly related to the subsurface electromagnetic velocity.

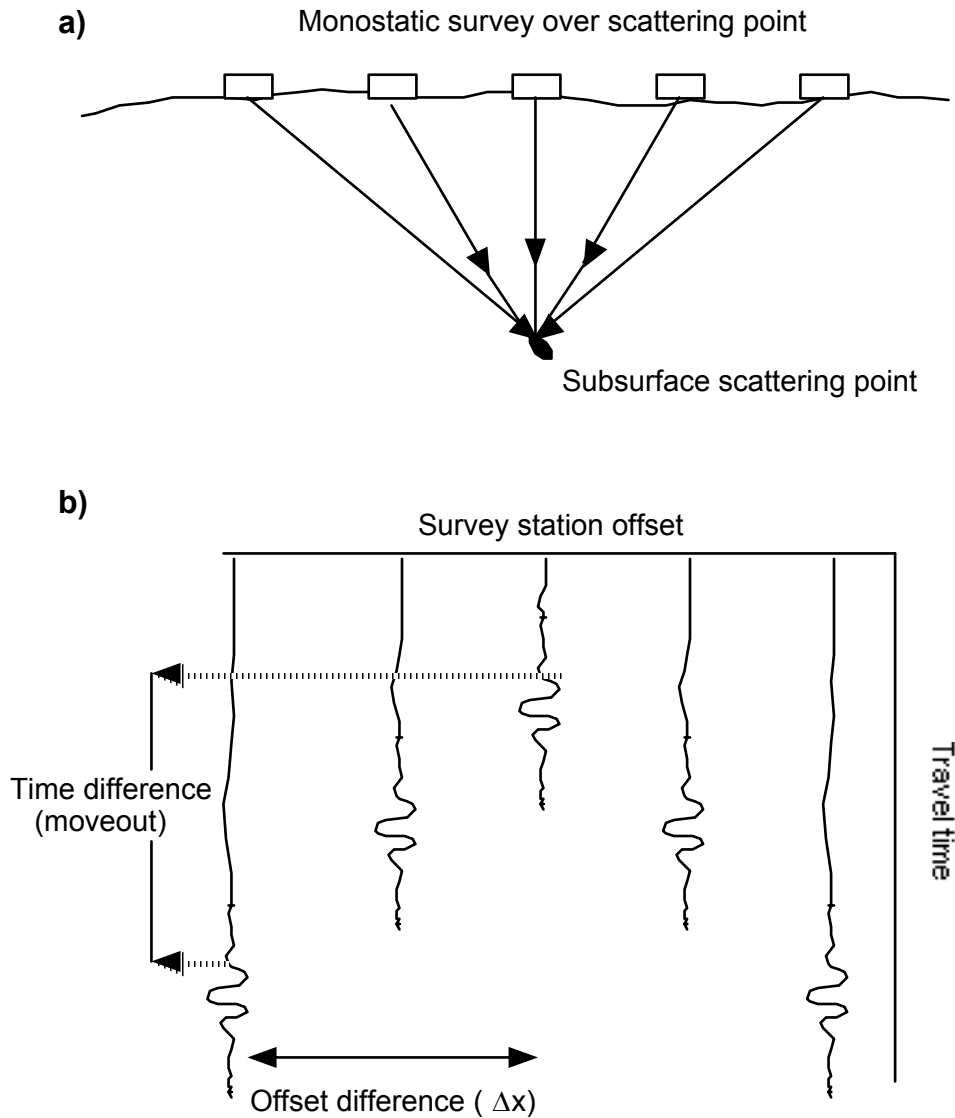


Figure 5. (a) Monostatic GPR survey over a point inhomogeneity in subsurface; (b) associated radar recordings. The time difference for the arrival of the diffracted signal as a function of survey offset (horizontal position) is determined by the electromagnetic velocity of the subsurface.

Choice of antenna frequency

Because GPR transmitting antennae operate in the megahertz range, the waves that propagate tend to have wavelengths on the order of 1m or less. Horizontal and vertical resolution are dependent upon the wavelength, such that the smaller the wavelength, the better the resolution. Although higher frequency sources will yield smaller wavelengths (better resolution), the higher frequency signals will not penetrate as deep as lower frequencies. Thus a careful choice must be made regarding the GPR antennae to use in a survey based on expected target and the project goals.

Antenna frequency will effect the intrinsic resolution in both the vertical and horizontal directions. Resolution is a measure of the smallest separation that can be distinguished between discrete targets. Thus, a small resolution is in fact better than a large resolution. Vertical resolution is based primarily on the wavelength (velocity of propagation divided by the dominant radar frequency) of the electromagnetic

energy, given simply as $1/4$ the wavelength. For example, given a material with dielectric constant of 9 (corresponding to an electromagnetic wave velocity of 0.1m/ns), a pulse transmitted at 200MHz would have a wavelength of 0.5m . For the same material, a pulse transmitted at 100MHz would have a wavelength of 1.0m . The vertical resolution for these cases would be 12.5cm and 25.0cm , respectively.

Horizontal resolution is affected by survey design (mentioned earlier) as well as the more intrinsic resolution related to the frequency content of the probing electromagnetic wave. The survey method (monostatic versus bistatic) will determine the lateral variations that are able to be imaged (i.e., those larger than the horizontal sample rate), whereas the lateral averaging introduced due to the propagating wavefield will be dependent on the dominant wavelength and the depth of investigation. The farther the target is from the source, the larger the wavefield “footprint”, the worse the resolution (Figure 6). For a wavefield with a wavelength of 0.5m as in the last example, the horizontal resolution at 2meters depth would be $R=1\text{m}$, at 10meters depth R would be $\sim 2.236\text{m}$, and at 100m depth $R\sim 7.071\text{m}$.

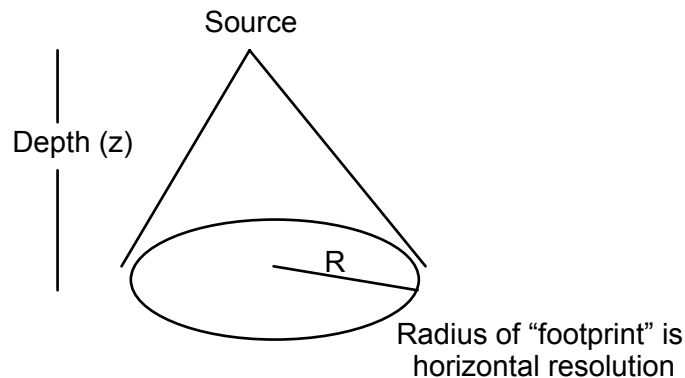


Figure 6. An electromagnetic wave with dominant frequency given by f and traveling at velocity v will have a finite “footprint” at a distance z from the source

$$R \cong \sqrt{z \frac{v}{f}}$$

In-field signal enhancement

During data acquisition, multiple radar scans are normally taken at each survey location. These scans are then summed (stacked) together to reduce incoherent noise in favor of coherent reflection or diffraction signals. This averaging is normally done explicitly with bistatic antennae, so that at each survey location the recorded radar data trace is commonly a stack of as many as 128 scans.

With monostatic GPR, a scan rate (scans/s) is normally chosen by the operator, and in field stacking can also be implemented by most instruments so that each recorded trace will be a stack of more than one radar scan. However, because the monostatic unit is in motion (pulled along the survey line), the stacked data will actually incorporate some lateral averaging, as each scan in the stack will be over a slightly different survey position (related to the speed of acquisition). When the rate of acquisition is known (m/s), this lateral averaging can be estimated by dividing the scan rate by the acquisition rate to yield the number of scans per meter. As an example, if a monostatic unit is collecting data at 36scans/s with an acquisition speed of 1m/s , then the number of scans per meter is 36. With a stacking rate of 18 scans/record, the lateral averaging would be across half of a meter.

Monostatic versus bistatic

The different methods for common offset data collection and signal enhancement described above (continuous versus discrete) are not fundamental differences between monostatic and bistatic radar systems. They are practical differences. The monostatic unit can be used in a discrete acquisition mode, but its strength is in the ability to perform rapid surveying in a continuous mode. A pair of bistatic antennae can be set in a frame that allows the operator to pull the unit in a continuous acquisition mode, but its

strength is in data enhancement at the discrete locations. The discussion to follow associates monostatic radar with continuous acquisition and bistatic radar with discrete acquisition.

NORMAL PROCESSING

Some survey questions (e.g., anomaly detection) can be answered in the field by looking at the raw GPR data. However, most often data undergoes a series of simple processing steps (filtering operations). The basic processing is slightly different depending upon the type of GPR system. Monostatic systems require a little more massaging of the raw field records.

Monostatic processing

- 1) zero-time adjust (static shift) -- need to associate zero-time with zero-depth, so any time offset due to instrument recording must be removed before interpretation of the radar image.
- 2) subtract average trace to remove banding -- need to remove the ringing that is inherent in monostatic units due to the close proximity of the source and receiving antennae
- 3) horizontal (distance) stretch to get constant trace separation (horizontal normalization) -- need to remove the effects of non-constant motion along the profile. Data are collected continuously, and will not be represented correctly in the image if steps are not taken to correct for the variable horizontal data coverage.
- 4) gain -- need to compensate for amplitude variations in the GPR image; early signal arrival times have greater amplitude than later times because these early signals have not traveled as far. The loss of signal amplitude is related to geometric spreading as well as intrinsic attenuation. Various time-variable gain functions may be applied in an effort to equalize amplitudes of the recorded signals.

Bistatic processing

- 1) zero-time adjust (same as for monostatic)
- 2) gain (same as for monostatic)

ADVANCED PROCESSING

Other filtering operations can be applied to GPR data. Many of these advanced techniques are used routinely in processing seismic data (Yilmaz, 1987). The most common processing steps that might be applied to GPR data would be lateral averaging, frequency filtering, deconvolution, and migration.

Lateral averaging

At each station in a bistatic GPR survey, the data record consists of one trace, with the signal recorded for a certain length of time, where the greater the time window, the greater the potential depth of imaging. Lateral averaging can be used across each trace to improve signal (reflection) coherency. This lateral averaging is most effective, however, for a monostatic survey where the horizontal sample rate is large (small horizontal sample interval). Lateral averaging (stacking, or summing data traces directly) can improve the ratio of signal to noise. For example, with a monostatic survey collecting data at 40 traces/m (which is a lot of data!), the extra data can be used more effectively in a lateral averaging step than leaving the interpreter to study the complex variation on the order of 1/40th of a meter.

Frequency filtering

Although GPR data are collected with source and receiver antennae of specified dominant frequency, the recorded signals include a band of frequencies around the dominant frequency component. Frequency filtering is a way of removing unwanted high and/or low frequencies in order to produce a more interpretable GPR image. High-pass filtering maintains the high frequencies in the signal but removes the low frequency components. Low-pass filtering does just the opposite, removing high frequencies and retaining the low frequency components. A combination of these two effects can be achieved with a band-

pass filter, where the filter retains all frequencies in the pass band, but removes the high and low frequencies outside of the pass band.

Deconvolution

When the time-domain GPR pulse propagates in the subsurface, convolution is the physical process that describes how the propagating wavelet interacts with the earth filter (the reflection and transmission response of the subsurface). Deconvolution is an inverse filtering operation that attempts to remove the effects of the source wavelet in order to better interpret GPR profiles as images of the earth structure. Deconvolution operators can degrade GPR images when the source signature is not known.

Deconvolution operators are designed under the assumption that the propagating source wavelet is minimum phase (i.e., most of its energy is associated with early times in the wavelet). This assumption is not necessarily valid for GPR signals. With GPR, the ground becomes part of the antennae, and the source pulse can vary from trace-to-trace and is not necessarily minimum phase. All filtering operations borrowed from seismic data processing must be applied with care as some of the underlying assumptions for elastic waves generated at the surface of the earth are not valid or are different for electromagnetic waves.

Migration

Migration is a processing technique which attempts to correct for the fact that energy in the GPR profile image is not necessarily correctly associated with depths below the 2-D survey line (approximation #2 above). As with deconvolution, migration can be seen as an inverse processing step which attempts to correct the geometry of the subsurface in the GPR image with respect to the survey geometry. For example, a subsurface scattering point would show up in a GPR image as a hyperbolic-shaped feature (similar to Figure 5). Migration would associate all the energy in the wavelets making up the hyperbolic feature with the point of diffraction, and imaging of the actual earth structure (the heterogeneity represented by the point diffractor) would be imaged more clearly. Migration operators require a good estimate of subsurface velocity structure in order to apply the correct adjustments to the GPR image.

INTERPRETATION

If the subsurface was perfectly homogeneous, the GPR unit would not record any reflections. Thus, the fact that the earth is heterogeneous gives us radar reflection data to interpret. We associate radar reflections with changes in dielectric constant, which in turn are related to changes in soil or rock bedding, buried man-made objects, geologic intrusives, void space, fractures, clay type, and moisture content. Because an increase in moisture content dramatically reduces radar propagation velocity (increases dielectric constant), the average dielectric constant is often proportional to the water saturation of the soils/rock in the subsurface.

When the propagating source pulse passes through the heterogeneous earth, reflections are sent back to the surface where the receiving antenna records a scaled version of the source wavelet. This scaling is related to the reflection coefficient, which is a function of the dielectric contrast that describes the inhomogeneity encountered by the traveling wave. The deeper the inhomogeneity, the longer it takes for the scattered energy to travel back to the surface. Thus, when the antenna measurements are plotted with respect to time, information in the signal at later times is associated with greater depths. As the survey progresses, data are collected with respect to profile distance and measurements in each recording (trace) are associated with depth below the surface. In this way the GPR data represent an image of the subsurface structure. The radar propagation velocity is proportional to the square root of the dielectric constant. With a good estimate of the propagation velocity, images with respect to travel time (two-way travel time down and back to the surface) can be transformed directly to images with respect to depth. Propagation velocities can be estimated with bistatic CMP GPR data alone; however, for monostatic data, and to get the best values, some sort of ground truth is used to correlate the GPR time data with depth. Once this is done, the electromagnetic propagation velocity can be calculated.

Figure 7 displays GPR data over a heterogeneous sand and gravel aquifer from both a monostatic survey and a bistatic survey. The coherent reflection in both images at 200-300ns is the basal clay aquitard. Structure within the overlying aquifer appears slightly different in the two GPR profiles. There is a

little more vertical resolution achieved with the monostatic radar, even though the nominal dominant frequency is less than that of the bistatic unit for this particular example. Otherwise, data look very similar. One thing to note is that the bistatic data were collected with a station interval of 1 meter. The monostatic data in Figure 7 were plotted at 1 trace/m, but were actually recorded at about 40 traces/m. The fine horizontal sampling of the monostatic unit can be used to interpret smaller lateral changes. Where the gross structure is important, the extra data can be averaged to improve the coherent signal (reflections).

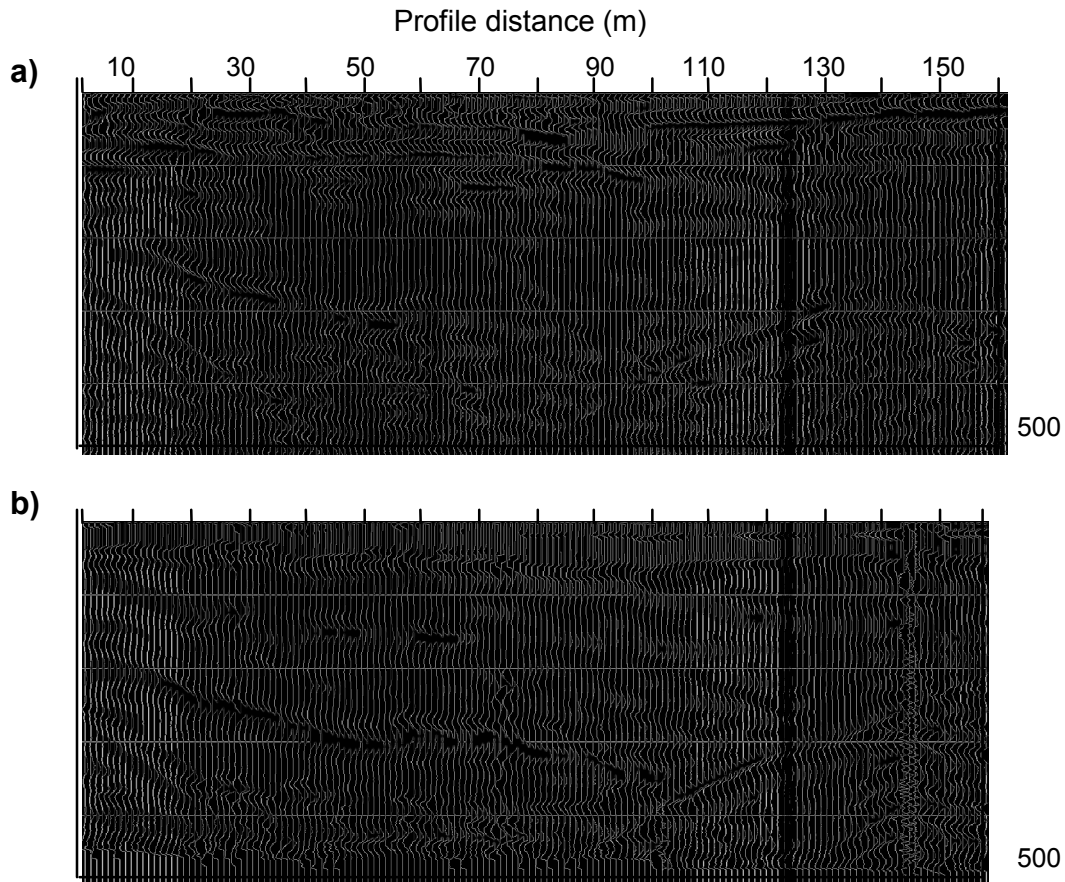


Figure 7. a) Monostatic radar profile of a shallow sand and gravel aquifer (data collected at ~40 traces/m, only every 40th record plotted) ; b) bistatic radar profile coincident with monostatic profile (data collected and plotted at 1 trace/m). The monostatic antennae had a nominal dominant frequency of 20 MHz; the bistatic antennae had nominal dominant frequency of 25MHz.

Electromagnetic wave velocity decreases with depth (in general), so that the theoretical resolution increases with depth as described earlier. However, this improvement is offset by the loss of high frequencies in the signal as it propagates which effectively reduces resolution. Attenuation is dependent upon conductivity, and increases with increasing frequency. Good radar media implies low conductive attenuation. On the other hand, a poor radar media implies higher conductivity which attenuates signal and reduces penetration. Table 2 shows some common examples of good and poor radar media.

Table 2

<u>Good radar media</u>	<u>Poor radar media</u>
dry salt	salt water
snow	metals
ice and fresh water	clay
peat	clay-rich soils
wet or dry sand	conductive minerals
dry rocks	

To summarize, the deepest penetration will occur in dry, nonclayey soils, and in dry rocks with no clay cementation. Snow and ice cover (and permafrost) will not adversely affect GPR data. When the soils or rocks are saturated, the conductive nature of the filling liquid becomes important. Fresh water is the most favorable for radar penetration.

Figure 8 displays examples of bistatic radar profiles collected with three different transmitter source frequencies, 200, 100 and 50MHz. All three profiles in Figure 8 were collected along the same survey line over a heterogeneous sand and gravel aquifer. The increased shallow resolution for the higher frequencies, offset by the shallower depth of penetration is evident. The recording time windows for the three different surveys in Figure 8 were different, based on the expected increase in depth of penetration with decreasing dominant frequency. Although measurements were recorded for longer than 100ns with the 200MHz source, clearly there is no coherent signal in the deeper portion of the image. Similarly, for the 100MHz source. Although data were collected beyond 150ns, there is no coherent signal from depths associated with those times. In contrast, there appears to be signal well into the deepest portions of the 50MHz GPR image.

The soil stratigraphy displayed in the radar images of Figure 8 correlate across each profile. However, the higher frequencies in the 200MHz image offer the best vertical resolution. The 100MHz image has intermediate resolution, and the 50MHz image shows the grossest structural variation.

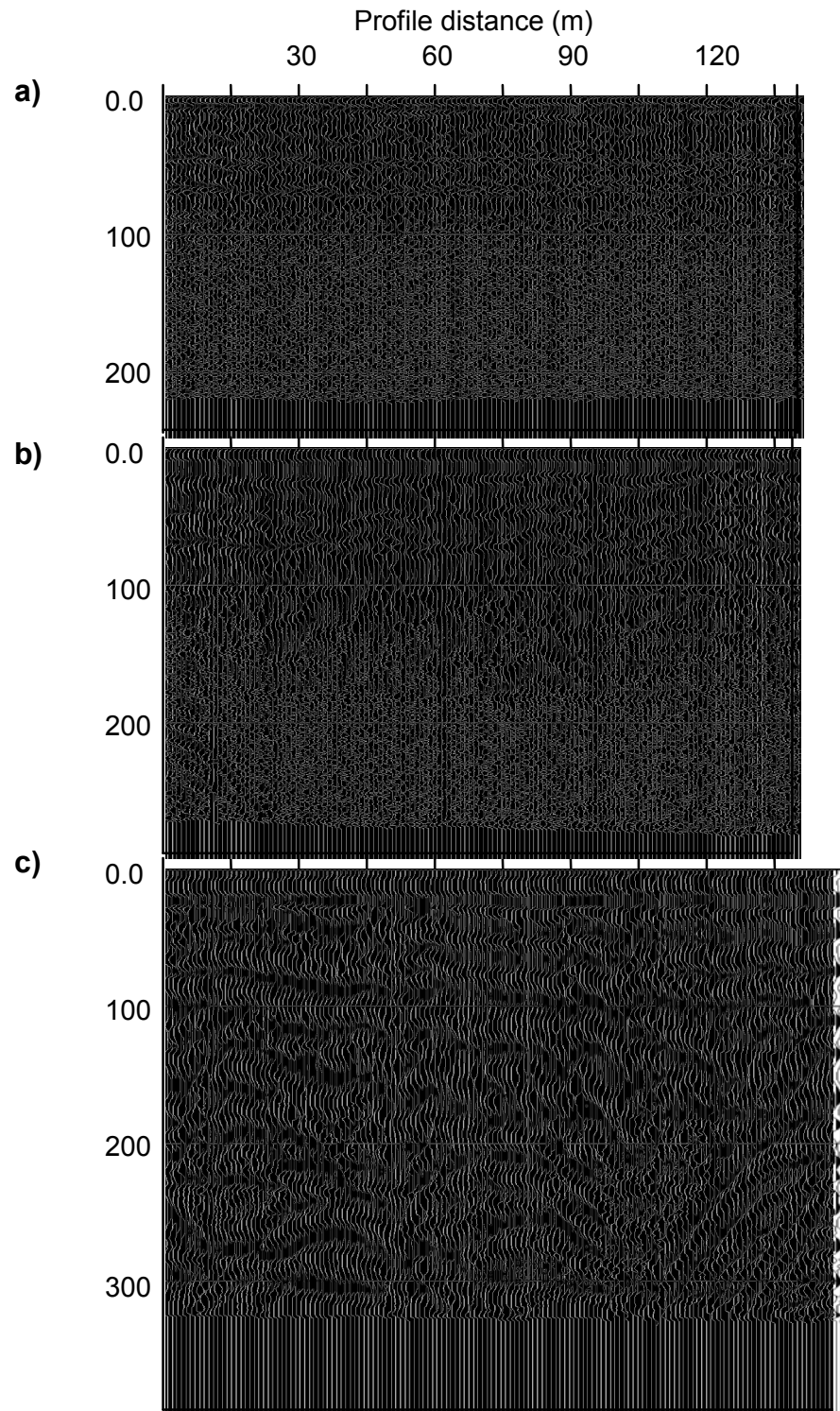


Figure 8. Radar profile images along same survey line for three different antenna frequencies: a) 200MHz, b) 100MHz, and c) 50MHz. Note decrease in vertical resolution from 200-50 MHz, but increase in depth of penetration.

Qualitative interpretation of GPR profiles is fairly straightforward, because the data are displayed in a cross-section, or image plane. Soil and/or rock structural variation as a function of survey position and relative depth is readily seen. In addition, certain GPR signatures can relate to specific underground targets:

- attenuation losses related to conductive regions (clays, increased saturation)
- distinct natural layering versus chaotic in-filled trenches or excavation areas
- reflection strength variation may relate to changes in conductivity
- diffractions from point scatterers

Ground truth is critical for helping to determine electromagnetic wave velocities for time-to-depth conversion, as mentioned earlier. Ground truth is also important for correlating GPR signatures with specific underground targets for a given survey. There are two major things that will cause problems when interpreting GPR data: the presence of clay minerals and very inhomogeneous materials.

Clay minerals

When clay minerals are present in the rocks and soils, dissolution will create ionic solutes. These ions become mobilized in saturated pore space, and conductivity increases. The presence of clay minerals will tend to increase conductivity and thus increase the amount of conductive attenuation. It is hard for radar to "see through" clayey soils.

Very inhomogeneous materials

When materials are extremely inhomogeneous, coherent reflections will be hard to find in the GPR images. Instead, the recorded signals will be made up primarily of diffraction (scattered) energy. The scattering can often be related to point inhomogeneities (diffractors, or scatterers) in subsurface and/or above ground, and the diffraction apex can give information about the point diffractors; although true analysis of this sort requires 3-D visualization/interpretation. Diffractions are only clearly represented in 2-D if the survey is perpendicular to a 2-D object (e.g., a buried pipe). Otherwise, the electromagnetic radiation travels in all directions away from the source, not just in the plane described by the horizontal survey coordinate and the depth of investigation. This energy will be scattered off of discontinuities that are not directly below the survey line, but the energy will still be recorded by the receiver. Plotting the data in 2-D cross-sections is truly a matter only of convenience. Care must be taken during interpretation as some of the features in the 2-D profile of subsurface structure will be artifacts due to the energy scattered from outside the imaging plane. If lateral inhomogeneity is too strong, there may not even be any coherent diffractions from specific point scatterers to interpret.

Forward modeling of electromagnetic waves in lossy (attenuative) dielectric media can be helpful for qualitative and quantitative interpretation. Quantitative information can also be obtained with limited ground truth or along with interpretation of other geophysical data sets.

CONCLUSION

The GPR method records microwave radiation that passes through the ground and is returned to the surface. A transmitter sends a microwave signal into the subsurface, and the radar waves propagate at velocities that are dependent upon the dielectric constant of the subsurface medium. Changes in the dielectric constant that are due to changes in the subsurface materials cause the radar waves to reflect, and the time it takes energy to return to the surface relates to the depth at which the energy was reflected. Thus, interpretation of this reflected energy yields information on structural variation of the near subsurface. Data are most often collected along a survey profile, so that plots of the recorded signals with respect to survey position and travel-time can be associated with images of geologic structure as a function of horizontal position and depth. Ground penetrating radar can be collected fairly rapidly, and initial interpretations can be made with minimal data processing, making the use of ground penetrating radar for shallow geophysical investigation quite cost-effective.

Detailed structural interpretation can be important for hydrological and geotechnical applications such as determining soil and bedrock characteristics in the shallow subsurface. In addition, high-resolution imaging is important for monitoring structural integrity of buildings, mine walls and roadways and bridges. Ground penetrating radar (GPR) is the only geophysical technique that can offer the horizontal and vertical

resolution necessary for many of these applications. The GPR method can be used for reconnaissance (anomaly location) as well as for the more detailed studies.

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